AFRL-HE-WP-TR-2005-0165

STINFO COPY

AIR FORCE RESEARCH LABORATORY

Battlespace Logistics Readiness and Sustainment Research

John T. Jacobs

Northrop Grumman Information Technology
2555 University Blvd.
Fairborn, OH 45324-6501

January 2005

Final Report for June 2003 to January 2005

Human Effectiveness Directorate
Warfighter Readiness Research Division
Logistics Readiness Branch
2698 G Street
Wright-Patterson AFB OH 45433-7604

NOTICES

TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-2005-0165

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

//SIGNED//

DANIEL R. WALKER, Colonel, USAF
Chief, Warfighter Readiness Research Division
Human Effectiveness Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
January 2005	Final	June 2003 - January 2005

4. TITLE AND SUBTITLE
Battlespace Logistics Readiness and Sustainment Research

5a. CONTRACT NUMBER
F33615-99-D-6001 DO#26

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
63231F

6. AUTHOR(S)
John T. Jacobs

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
49230208

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Northrop Grumman Information Technology
2555 University Blvd.
Fairborn, OH 45324-6501

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Materiel Command
Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Readiness Research Division
Logistics Readiness Branch
Wright-Patterson AFB OH 45433-7604

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-HE-WP-TR-2005-0165

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Battlespace Logistics Readiness & Sustainment Research was an effort initiated by the Air Force Research Laboratory's Logistics Readiness Branch (AFRL/HEAL) to provide specialized research to develop and evaluate logistics technologies. Within the scope of this program specific research tasks could be focused on feasibility studies, cost benefit analyses, modeling and simulation data and algorithms, front-end analyses, field test support activities, and demonstration system development within the domains of operational, contingency, and acquisition logistics. Operational logistics emphasizes improving the performance of logistics personnel in all operational environments. Contingency logistics encompasses technologies to improve the speed, efficiency and ease of deployment of all logistics support elements necessary to support contingency operations. Acquisition logistics focuses on improving the logistics elements of systems during development through improved system design support and information technologies.

15. SUBJECT TERMS
Logistics, Maintenance, Prognostics, Diagnostics, Operational, Contingency, Acquisition

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Edward S. Boyle
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	16	**19b. TELEPHONE NUMBER** *(include area code)* 937-255-5169

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

20051206 056

THIS PAGE LEFT INTENTIONALLY BLANK

PREFACE

The research documented in this technical report for the Battlespace Logistics Readiness and Sustainment program was sponsored by the Air Force Research Laboratory, Human Effectiveness Directorate, Logistics Readiness Branch (AFRL/HEAL), Wright-Patterson AFB, OH. The research was conducted under Delivery Order #26 of the Technology for Readiness and Sustainment (TRS) contract (F33615-99-D-6001). The University of Arkansas, Department of Industrial Engineering performed the work with the assistance of Northrop Grumman Information Technology. Edward S. Boyle (AFRL/HEAL) was the program manager for this effort.

Table of Contents

1. Introduction

The Battlespace Logistics Readiness & Sustainment Research was an effort initiated by the Air Force Research Laboratory's Logistics Readiness Branch (AFRL/HEAL) to provide specialized research to develop and evaluate logistics technologies. Within the scope of this program specific research tasks could be focused on feasibility studies, cost benefit analyses, modeling and simulation data and algorithms, front-end analyses, field test support activities, and demonstration system development within the domains of operational, contingency, and acquisition logistics. Operational logistics emphasizes improving the performance of logistics personnel in all operational environments. Contingency logistics encompasses technologies to improve the speed, efficiency and ease of deployment of all logistics support elements necessary to support contingency operations. Acquisition logistics focuses on improving the logistics elements of systems during development through improved system design support and information technologies.

After reviewing a wide range of logistics challenges and research requirements, and assessing the budget realities, AFRL/HEAL decided to narrow the actual research that would be conducted to the five areas of interest listed below.

- Modeling Sortie Generation for Unit-Level Logistics Planners
- Maintenance Decision-Making under Prognostic and Diagnostic Uncertainty
- Quantifying the Impacts of Improvements to Prognostic and Diagnostic Capabilities
- Multi-State Selective Maintenance Decisions
- Quantification of Logistics Capabilities

Tasks covering each of those five areas were developed and packaged as a delivery order that was performed over an 18 month period by the University of Arkansas, Department of Industrial Engineering, with the assistance of Northrop Grumman, under AFRL's Technology for

Readiness and Sustainment (TRS) research contract with Northrop Grumman. Individual reports were written detailing the research conducted on each task.

2. Modeling Sortie Generation for Unit-Level Logistics Planners

This research demonstrated that simulation could provide valuable information for decision-making at the unit-level and provide much needed assistance in the generation and execution of a weekly flying schedule. In research performed by the University of Arkansas on a previous TRS delivery order, a simulation model detailing an Air Force Multi-Indenture Multi-Echelon (MIME) [McGee, 2004] repairable parts system was developed. That simulation model was used to explore the effects of using commercial shipping practices on the supply chain. This research expanded the simulation model developed for the commercial transportation project to detail the sortie generation process. Using this simulation the effective risk inherent in a given weekly schedule was evaluated. The concept was to allow until-level logistics planners to input a weekly schedule and to evaluate that schedule based on outputs received from the simulation. A model of this type also allows the unit-level logistics planners to compare alternative schedules and perform what-if analysis.

There are significant challenges in developing a tool that is useful at the unit-level. First, the user interface must be such that the planners can quickly and easily input the needed data. If the user interface is too complex or confusing no value will be added to the decision process. Second, the simulation must be detailed enough to provide useful outputs to the user, but also simple enough that the simulation time and data requirements are minimal.

This research began by reviewing the relevant literature, systems, and processes. Part of the goal was to illustrate how simulation could be used in this context. Thus, military logistics, MIME

systems, and user interface systems required review. Likewise, the project provided a detailed description of the simulation model along with the user interface system and a description of data handling methods. In addition, a test scenario was outlined along with detail on how the model handles this scenario from user input to interpreting the output data. Examples of what-if analysis that can be performed using the same test scenario were also developed. Through the execution of this test scenario, the research demonstrated how this type of simulation technology could be useful in making decisions at the unit-level. The outputs will provide the user valuable assistance in making timely decisions that can mitigate the risk associated with executing a flying schedule.

3. Maintenance Decision-Making under Prognostic and Diagnostic Uncertainty

A key challenge faced by USAF maintenance personnel is the uncertainty associated with the information provided by many of their diagnostic tools. This uncertainty results from precision and accuracy issues associated with individual diagnostic tools, as well as inconsistencies between different diagnostic tools (such as different testing parameters embedded in aircraft built-in-test (BIT) systems for a component versus the parameters in the test sets used by flightline and shop technicians to troubleshoot that same component). This uncertainty can make it very difficult for maintenance technicians to choose an appropriate course of action. The end result is the possible omission of necessary maintenance actions and/or the performance of unnecessary actions. Both of these potential mistakes can cause delays in returning an aircraft to mission capable status and increased requirements for spare parts in the supply chain.

This research developed a methodology based on mathematical modeling that can be used to synthesize the diagnostic information and provide a recommended course of action to the

technician. Ultimately, this methodology could potentially be incorporated into a decision-support tool for the technician.

This research was conducted using a hypothetical weapon system; however, that hypothetical weapon system was defined such that it possesses fundamental characteristics similar to systems utilized by the U.S. Air Force. Modeling-based methodologies were developed for synthesizing diagnostic information and providing an estimated assessment of the system. A Bayesian probability approach was defined for synthesizing imperfect and conflicting diagnostic information, along with the characteristics of the system of interest and the diagnostics applied to that system.

The research demonstrated how a Bayesian analysis could be used to provide an assessment of system status, and using a numerical example, demonstrated the potential effectiveness of the approach. First, the system structure and the reliability and maintainability characteristics of each component in the system were defined. Second, the characteristics of the diagnostic tools applied to the system were identified. This identification included a description of the precision and accuracy in diagnostic information. Third, a set of mathematical and logical models were developed which synthesized the diagnostic information and provided an estimated assessment of the system. Finally, numerical experiments were utilized for assessing the capabilities of the defined models.

The Bayesian approach showed great promise as a means of compiling imperfect and conflicting diagnostic information; however, that approach requires exact monitoring of component aging and perfect life distribution estimation. Furthermore, that approach requires an assumption of independent component failures. Therefore, an alternative approach based on artificial neural networks (ANN) was explored. This approach does not suffer from either of the

identified limitations of the Bayesian approach; however, the numerical results associated with this approach were not as promising. The specifics of the research and the methodology used, along with the mathematical calculations, are detailed in a separate project report.

4. Quantifying the Impacts of Improvements to Prognostic and Diagnostic Capabilities

A key challenge faced by USAF maintenance personnel is the imperfection of aircraft diagnostic and prognostic capabilities. These imperfections include an inability to pinpoint failed components, the incorrect identification of failed components, and "Could Not Duplicate (CND)" or "Retest Okay (RETOK)" errors between flightline and shop tests and between base-level and depot tests. These imperfections lead, among other things, to increased delays in returning aircraft to mission capable status and to excessive spare parts requirements. Unfortunately, it is difficult to assess the impact of improvements to diagnostic and prognostic capabilities.

This research developed a methodology based on mathematical modeling for analyzing those impacts. Specifically, the following questions were addressed: (1) What impact does diagnostic and prognostic errors have on fleet readiness and the associated requirements for spare parts investment? (2) Given a specific investment in diagnostic and prognostic improvements, what will the impact be on fleet readiness and spare parts inventory measures? (3) Given a limited budget for diagnostic and prognostic improvements, how should the funds be allocated to optimize fleet readiness and spare parts inventory measures?

As in the Maintenance Decision-Making under Prognostic and Diagnostic Uncertainty research discussed above, this research utilized hypothetical systems that possessed key characteristics similar to those utilized by the U.S. Air Force. In the first phase of the project, a

set of mathematical and logical modeling tools related to diagnostic errors was created. A modeling framework for a single system was established, and simulation modeling efforts were described for evaluating the readiness of a single system and a set of systems under diagnostic errors. In addition, an optimization model for allocation of a diagnostic improvement budget was presented.

In the second phase of this research, a simulation modeling environment to compare prognostics to scheduled maintenance was used. As a first step, the system structure and the reliability and maintainability characteristics of each component in the system were defined. Second, the characteristics of the diagnostic and prognostic tools applied to the system were identified. This identification included a precise description of the potential for imperfections in diagnostic and prognostic information. Third, a set of mathematical and logical models was developed that could be used to measure the performance of the fleet with and without diagnostic and prognostic errors. This permitted assessment of the impact of diagnostic and prognostic imperfections on fleet readiness and spare parts inventory investment. Specifically, it was shown that prognostics could be an effective tool in some cases (even in the presence of significant prognostics errors) and a very ineffective tool in other cases. In some cases, prognostic errors could make a situation worse than if the system were simply run until it failed. Fourth, this model was used to explore the impact of specific investments in diagnostic and prognostic tools. That permitted evaluation of the cost-effectiveness of potential diagnostic and prognostic improvement actions. Finally, the model was incorporated into a decision-support environment designed to allocate investments in diagnostic and prognostic improvements. That permitted the decision-maker to fund cost-effective diagnostic and prognostic improvement efforts that optimized fleet performance.

5. Multi-State Selective Maintenance Decisions

All military organizations depend on the reliable performance of repairable systems for the successful completion of missions. The use of mathematical modeling for the purpose of modeling repairable systems and designing optimal maintenance policies for those systems has received an extensive amount of attention in the literature. Unfortunately, the vast majority of that work ignores potential limitations on the resources required to perform maintenance actions. That shortcoming has motivated the development of models for selective maintenance, the process of identifying the subset of actions to perform from a set of desirable maintenance actions. Previously, researchers have developed a class of mathematical models that can be used to identify selective maintenance decisions for the following scenario:

> *A weapon system has just completed a mission and will begin its next mission soon. Maintenance cannot be performed during missions; therefore, the decision-maker must decide which components to maintain prior to the next mission.*

The selective maintenance models considered to date treat decision-making for binary-state systems—all components, subsystems, and the system itself are assumed to be either functioning or failed at any point in time. As a result, mission reliability was used as the objective function in the resulting mathematical programming models.

This research improved upon that approach in two ways. First, it is more realistic to classify component status using more than two discrete levels (if not some continuous measure). This implies multi-state measures of subsystem and system status as well. Thus, this research developed a modeling-based methodology for managing selective maintenance decisions when multiple (more than two) system states are possible. Second, the performance of a military

system typically can be measured using several measures in addition to mission reliability. All these performance measures are functions of the status of the components. This research developed multi-state selective maintenance models that incorporate multi-state component status and multiple measures of system performance.

A scenario was defined in which systems in various states of maintenance need must perform a number of different missions. First, the system structure and appropriate status measures were defined for each component in the system. Second, the resources consumed by maintenance actions, the impact on component status of each potential maintenance action, and the quantity of each resource consumed by each maintenance action were identified. Third, the relevant measures of mission performance were identified and functions were developed that captured those measures in terms of the component status values. Fourth, a mathematical formulation of the selective maintenance problem was developed. Finally, solution procedures were developed to solve the selective maintenance problem. Enumerative solution strategies for smaller problems and heuristic strategies for larger ones were defined. This effort clearly advanced the state of the art in selective maintenance decision-making.

6. Quantification of Logistics Capabilities

In 2001, the Air Force Journal of Logistics published research findings by Oliver, et al. [Oliver, 2001] that identified the key logistics and operational factors associated with aircraft mission capability (MC). In their research, correlation analysis was performed to identify the key factors associated with MC rates and various logistical factors (such as logistics functions and personnel) and operational factors (such as funding and environment) and their associated interactions. Regression analysis was used to explain and predict F-16 MC rates using quarterly

data from FY93-FY00. Personnel skill levels, cannibalization, and funding levels were found to be the most significant factors. These research findings led to the recognition that the USAF does not currently have a metric to relate maintenance (MX) personnel skill level to operational readiness.

Building upon Oliver's work, the objectives of this research further investigated the relationship between personnel skill level and mission capability and developed an associated metric and standard. Specifically, a metric that measures MC rate as a function of MX personnel skill levels was developed. Once the metric was determined, a standard for that metric was identified that set the metric value that the Air Force should strive to maintain as part of their operational goals. The relationships between MX personnel skill level and multiple utilization and reliability and maintainability performance measures were also examined.

The research methodology consisted of performing four analysis tasks for each dependent variable. The first task was to define how the variables would be used in the analysis. Ten independent variables were identified to MX personnel skill level including the count and percentage of 3-, 5-, 7-, and 9-Level maintainers. The dependent variables that were modeled included MC rate, four utilization variables, and three reliability and maintainability variables. The second task performed a correlation analysis between the dependent and independent variables. Building upon the second task, the third task constructed a set of candidate regression models for each of the dependent variables. The last task was to choose a final model for each dependent variable by examining the linear fit of the models, the efficiency of models, and adherence to model assumptions. During that analysis and selection process, it was determined that good regression models for flying hours and sorties (two of the utilization variables) could not be developed as a function of MX personnel skill level variables.

In order to demonstrate the final regression models, output was developed into a predicted results matrix or chart to show the effect of changes in personnel levels based on the dependent variable of interest. There were three possible representations based on the number of variables in the model:

- Single-variable graph
- Dual-variable matrix
- Triple-variable series of matrices

The model selected for MC rate contained two variables: percentage of 7-Level and 9-Level maintainers (adjusted R-Squared value of 80.7%). Therefore, the recommended metric was the percentage of 7-Level and percentage of 9-Level maintainers employed. Using the final model for MC rate, a matrix was constructed that indicated for given personnel values, whether MC rates could be expected to meet or exceed standards for the F-16C/D aircraft.

A software tool was created for the purpose of using the models in prediction scenarios. The tool has a user interface that allows the entry of possible values for personnel skill and manning levels. Those values are used as inputs to the chosen regression models, and the output for each performance measure is computed at run time. The tool provides an example of the usefulness of the regression models in planning situations.

Although limited in scope, this effort certainly lays the groundwork for follow-on research into a perplexing Air Force logistics dilemma.

7. References

McGee, Joshua B., Rossetti, Manuel D., & Mason, Scott J. (2004). Simulating Transportation Practices in Multi-Indenture Multi-Echelon (MIME) Systems. *Proceedings of the 2004 Winter Simulation Conference*, 5-8 December 2004, pp. 974-981.

Oliver, Steven A., Johnson, Alan W., White, Edward D. & Arostegui, Marvin A. (2001). Forecasting Readiness – Regression Analysis Techniques – Military Operations Readiness. *Air Force Journal of Logistics*, 25(3), Fall, 2001, pp. 1, 29-40.